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TRACTOR POWER TAKE-OFF TORQUE MEASUREMENT AND DATA ACQUISITION SYSTEM

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TECHNICAL NOTE:

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ABSTRACT. *With the mechanization of agricultural operations, agricultural machinery management has become an extensive research field. Sizing tractors and implements to provide the most efficient power transfer has become an ongoing process with advances in technology. Utilization of the rotational power transferred through gear trains from the tractor engine to the power take-off (PTO) shaft is one of the most efficient methods of power transfer to an implement. This research used commercially available torque sensors that were installed on a tractor PTO shaft for measuring the torque delivered to an implement. The torque sensor was calibrated using the Nebraska Tractor Test Lab's (NTTL) dynamometer by following the Organisation for Economic Co-operation and Development (OECD) Code 2 test procedure for varying PTO loads. The calibration of the sensor was verified using the full load at varying speeds test as described in the OECD Code 2. Tractor PTO shaft torque values measured by the torque sensor were compared to the NTTL's dynamometer torque measurement. Differences in torque values measured between the sensor and the dynamometer ranged from 3 to 23 N·m. Student's t-test showed no significant difference between the measurements during the full load varying speed tests which demonstrated that the sensor can be mounted on the tractor's PTO shaft for torque data collection in field operations.*

Keywords. *Data Acquisition, LabVIEW, Power Take-off, Torque, Tractor.*

Matching implements correctly to effectively utilize tractor power had been a continuing research pursuit with the advancements in machinery technology. The tractor transmits power to the implement through several systems independently: draft power is transferred via the drawbar or 3-point hitch, fluid power is available through one or more hydraulic remote blocks, rotational power is transmitted from the engine through a gear train to the power take-off (PTO) shaft, and electrical power is provided through multiple electrical outlets inside and outside the tractor cab. The most efficient transmission (~90%) of net engine power (*ASABE Standards,* ASAE D497.7, 2015) for an agricultural tractor to a towed implement requiring rotary power whether stationary or mobile is via the PTO shaft (fig. 1).

Significant changes have been made to the tractor's PTO power delivery since being commercially available for the first time in 1918 on International Harvester Company's (IHC) model 15-30 (Goering and Cedarquist, 2004). The 21-spline 1000 rev·min^{-1} shaft standard was created in 1958 followed by a 20-spline "large" 1000 rev·min^{-1} shaft in 1966 (Mayhew, 1994). A new 1000 rev·min^{-1} shaft with 22 splines was created and included in the latest ISO standard (ISO, 2014b). Currently, the ISO standard includes location and dimensions of the PTO shaft and coupler (ISO, 2014b), master shield, clearance zone, and general safety requirements (ISO, 2014a). The ISO 500-1 standard (ISO, 2014a) recommended the maximum PTO power transmitted at rated engine speed for each PTO type. Power and speed requirements of implements are calculated by the implement manufacturers and are dependent on drivetrains and implement load. Tractor manufacturers then anticipate and calculate which tractors are able to power these implement loads and install the appropriately sized PTO transmission. For example, Deere & Company offers the 540 rev·min^{-1} 35 mm shaft as the standard PTO type on their utility tractors up to the 6R series (132 kW, Deere & Company, 2016), and the 540 rev·min^{-1} 35 mm shaft is a standard on Case IH up to the Magnum series (152.9 kW, CNH Industrial America LLC, 2014).

Tractor PTO power measurement research using data acquisition systems (DAQs) have been performed utilizing fuel consumption data to determine total implement power (Sumner et al., 1986). Implements in the research included

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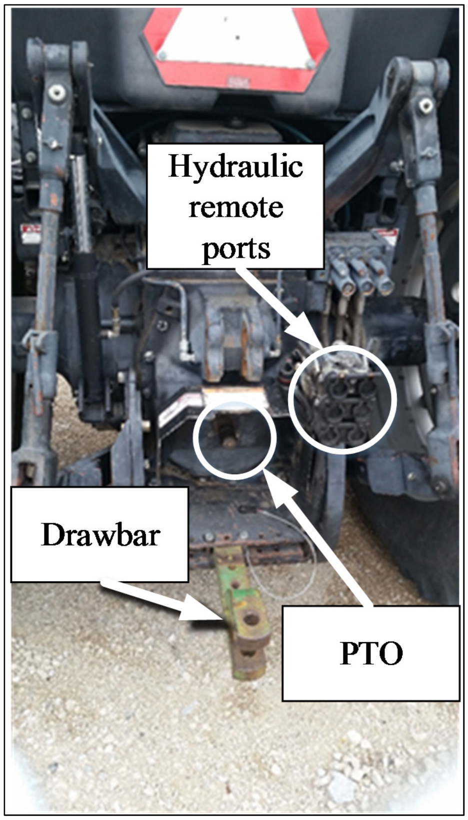


Figure 1. Typical location at the rear of an agricultural tractor for delivery of power to implements.

an IH mower-conditioner (990, International Harvester Co., Warrenville, Ill.), KMC two -row peanut digger (Kelly Manufacturing Co., Tifton, Ga.), peanut combine (1500, Lilliston Corporation, Albany, Ga.), NH 782 Forage Harvester (782, New Holland Machine Co., New Holland, Pa.) and 851 baler (851, New Holland Machine Co., New Holland, Pa.), and a Vermeer baler (605H, Vermeer Corporation, Pella, Iowa). Load differences between implement operations allowed the authors to estimate separate power requirements corresponding to draft power, PTO power, travel, and crop load as operated for 3 minutes or one bale depending on the mode. A study by Vigneault et al. (1989) used a torque meter secured to a cart to measure PTO power. The cart was connected to the tractor drawbar and the cart could attach to an implement via the implement drawbar or the implement 3-point hitch. Limitations of such a cart were the increase in overall machinery length and a possible safety hazard (e.g., overturns) due to tighter steering maneuvers. The cart did have benefits such as the ability to connect multiple PTO types using different shafts. Bending or shear stresses on the sensor shaft were also avoided by having universal joints on both shafts connected to the sensor. In another study, the implement PTO shaft was modified to include a built-in slip ring torque sensor for energy mapping (Kheiralla and Yahya, 2001). The modified shaft replaced the current shaft on the implement. This shaft was welded to a universal joint with a female coupler limiting the sensor to one size of PTO shaft without altering the universal joint and coupler. The rotary power table presented in table 2 of ASAE standard D497.7 (*ASABE Standards*, 2015) was based on the research of Rotz and Muhtar (1992). Many of the parameters in the table were the same values from the original research completed over 20 years ago. Not all of the rotary implements in the table have been vastly improved over the last two decades. However, with the increased implementation of embedded systems in agriculture [e.g., controller area network (CANBUS) and ISOBUS] variable rate application, and increased machinery size, some parameters in the ASABE standards may be outdated, and not representative of current equipment. A review of the rotary power requirement is needed for correctly matching the implements to the tractor. Properly matching the implement to the tractor allows the producer to make better management and purchase decisions based on operation size and budget.

This research presents a different approach to measure and verify PTO power delivered to an implement using OECD Code 2 test procedures to simulate field operating conditions. The approach used to complete this research utilized a commercially available slip ring torque sensor that involved no modifications to the tractor or implement PTO shaft. One of the requirements of the PTO torque sensor was the ability to fit on at least one standard PTO shaft size, allowing the sensor to be mounted onto tractors with the same size PTO shaft. This would maximize the number of tractors available for torque measurement and instrumentation while minimizing costs associated with modifications or replacement parts.

OBJECTIVES

The goal of this project was to develop a portable PTO torque and rotational speed measurement system that can attach to the tractor with no modifications to the tractor PTO shaft. Specific objectives of the research work were:

- to determine the calibration for the PTO torque sensor using the OECD Code 2 tractor PTO test procedure at varying loads with the Nebraska Tractor Test Laboratory dynamometer, and
- to use the OECD Code 2 tractor PTO full load at varying speed test procedures and the Nebraska Tractor Test Laboratory dynamometer to verify the calibration by determining if the sensor torque and power measurements were within 1% of the dynamometer.

METHODS AND MATERIALS

A PTO data acquisition system capable of measuring and recording torque and rotational speed was developed. The system was based on a commercially available instrumented slip ring torque sensor and data acquisition system used as the PTO device under test (DUT). Two torque sensors were evaluated and one was deemed appropriate for the DUT based on preliminary evaluation and testing.

PTO TORQUE SENSORS

Slip-ring torque sensors with flanged ends were easily obtained commercially. However, manufacturing couplers and shafts to mount these sensors in a compact package proved to be difficult. Ready-to-use PTO torque sensors were available from two vendors (Datum Electronics, United Kingdom and NCTE AG, Germany). These sensors had PTO couplers and shafts mated directly to the measurement shaft instead of having flanged ends. The connections used for this research were the 45 mm (1 ¾ in.) 1000 rev·min^{-1} 20-spline configuration shaft and coupler.

The Datum PTO system (Series 420, Datum Electronics, Ltd., East Cowes, Isle of Wight, United Kingdom) was a slip-ring based torque sensor with a quick attachment coupler. The quick attachment coupler had large tolerances that would allow the Datum torque sensor and the implement shaft to become eccentric as the shaft would rotate. This eccentric motion of the shaft caused a vibration to occur throughout the tractor. Safety concerns were raised, whether the vibration would limit the operational life of the Datum torque sensor electronics, or the sensor itself would fragment. Due to these safety concerns, the Datum torque sensor was not used for this research.

NCTE 7000 Torque Sensor for PTO Shafts

The NCTE torque sensor (7000 series, NCTE AG, Unterhaching, Germany) was a slip-ring based torque sensor with available flanged ends or a male and a clamp-type female PTO shafts (fig. 2).

Operating speeds of 3600 rev·min^{-1} and torque measurements of up to 5000 N·m were possible with this sensor. The sensor was factory set to an analog voltage output of 0-10 V. This voltage range was selected for expandable compatibility with further instrumentation of other implement parameter measurements.

The GKN coupler (601681, GKN Walterscheid GmbH, Lohmar, Germany) (fig. 2) had a robust clamping method. The recessed screw, one-piece split shaft GKN coupler used bolts threaded into the coupler to provide a high clamping force. With the GKN coupler the run-out at the rear of the sensor housing was 0.076 mm (0.003 in.) under no load and 0.381 mm (0.015 in.) when connected to the implement shaft. Vibration was present due to the eccentricity of the shaft, but the relative intensity was not atypical of agricultural implement operations.

Calibration Equipment and Test Setup

The Nebraska Tractor Test Lab (NTTL) provided a 522 kW Eddy Current dynamometer (the Dyno) (DM-2025DG, Dyne Systems Inc., Jackson, Wis.) as the calibration fixture. The resistance load created by the Dyno was measured by an Interface load cell (load cell) (1110BF-2K, Interface, Inc., Scottsdale, Ariz.). The load cell was an 8.90 kN (2000 lb_f) strain gage load cell (fig. 3a) on a lever arm with known distance from the rotational axis of the Dyno to provide a measurable torque independently from the controller calibrated torque of the Dyno (fig. 3b). There were two output circuits on the load cell to allow the Dyno controller and the measurement DAQ to have individual measurements. The Dyno and load cell were calibrated as a system semi-annually using procedures traceable to NIST.

The DAQ board used to read and record the signals from the NCTE torque sensor was installed inside the tractor cab. The laptop computer with the LabVIEW program used to obtain data from the DAQ board was situated away from the testing area behind a safety wall with a view of the test. The LabVIEW program was developed to measure the DUT voltage output corresponding to torque and the rotational speed. The DUT was secured to the shaft of the AGCO Allis tractor

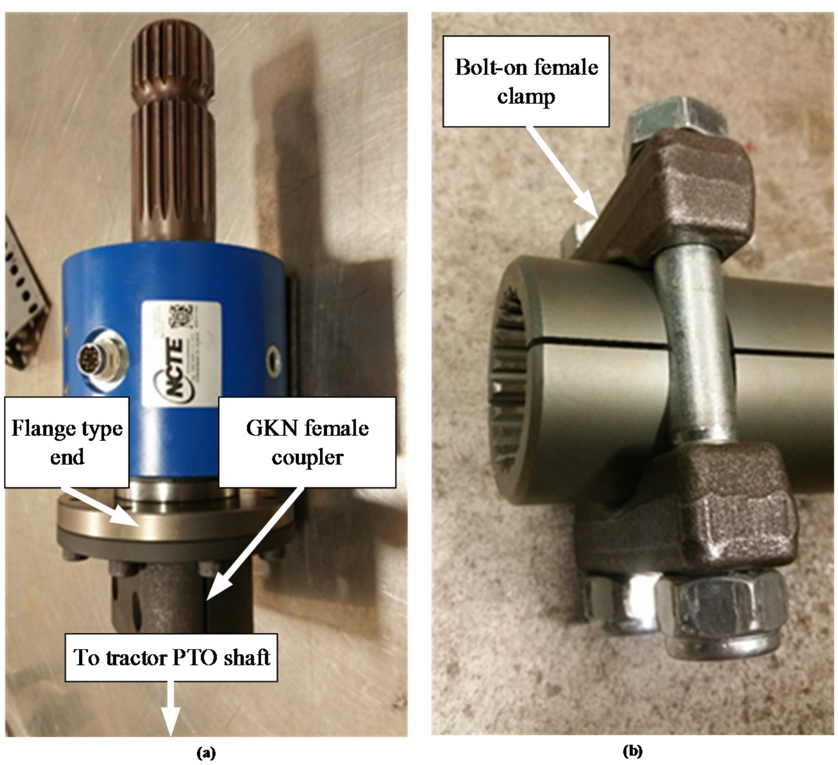
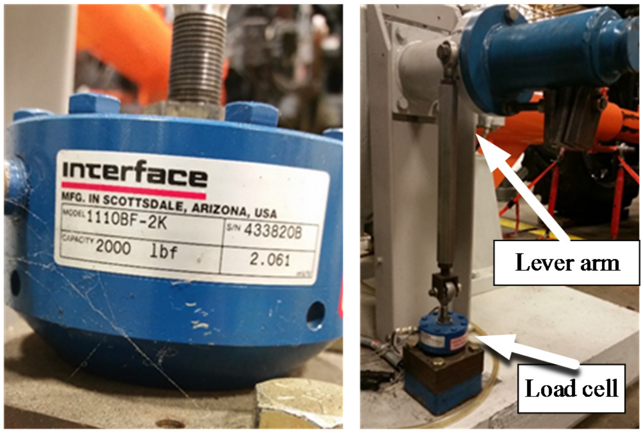


Figure 2. NCTE torque sensor with GKN female coupler.



(a) (b)

Figure 3. (a) ILC mounted to Dyno base, (b) ILC with known lever arm connected to Dyno.

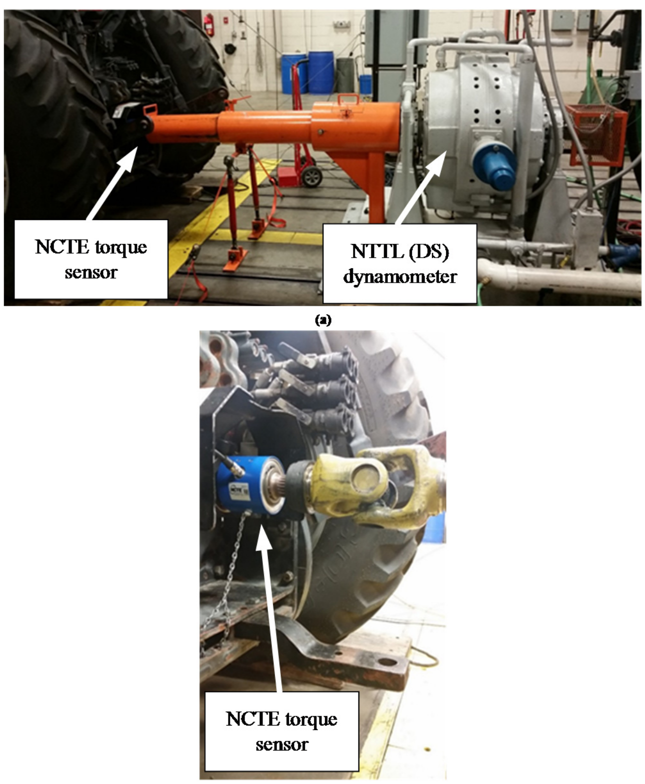
(9695, AGCO Corporation, Duluth, Ga.). A dial caliper was used to check the run-out on the implement shaft end of the DUT to ensure appropriate alignment between the mating parts. The DUT shaft end was attached to the Dyno (figs. 4a, 4b) via a GKN PTO shaft (GKN Walterscheid, Inc., Woodridge, Ill.).

DAQ Hardware and Software Program

Data acquisition from the NCTE torque sensor was accomplished using a National Instruments (NI) DAQ board (NI cDAQ 9174, National Instruments Corporation, Austin, Tex.). The DAQ was a portable 4-slot chassis for use with NI C series I/O modules. The chassis had the capability to handle multiplexed analog I/O, thermocouples, and digital I/O. A universal analog module (NI 9219, National Instruments Corporation, Austin, Tex.) capable of measuring analog voltages from amplified bridge strain gages, thermocouples, load cells, and other analog powered sensors, was used to measure the analog output of the DUT. The digital speed signal was measured and recorded using a digital input module capable of sinking or sourcing up to 4 digital input channels (NI 9435, National Instruments Corporation, Austin, Tex.). The Nebraska Tractor Test Lab's Dynamometer (The Dyno) used a digital multi-loop dynamometer controller (Dyno controller) (Inter-Loc V, Dyne Systems, Inc., Jackson, Wis.) to control the torque applied and the speed of the PTO shaft. The Dyno data acquisition board (NI cDAQ 9188, National Instruments Corporation, Austin, Tex.) was an 8-slot chassis with NI C series I/O modules to measure analog current (±20 mA) and analog input voltage (±10 V). Measurements of analog output voltage (±10 V), thermocouple (± 78 mV), high speed digital I/O (5 V), digital input (250 VAC/DC), and digital output (24 V) were achievable with the Dyno DAQ. An analog input channel was used to measure the torque applied to the load cell and the high-speed digital I/O used a counter to measure the pulses from the magnetic speed sensor of the Dyno. With the known number of pulses per revolution and a time clock on the recording computer, these measured pulses were used to calculate the rotation speed of the Dyno. The remaining analog and digital I/O channels were used to measure the other tractor operating parameters (e.g., intake temperature, oil pressure, engine speed, fuel flow rate).

Separate LabVIEW programs were utilized for the display and logging of the DUT DAQ and the Dyno DAQ data. The Dyno program was developed by the NTTL for official OECD tractor testing. The graphical user interface and control panel (front panel) of the virtual instrument (VI) used for the DUT during calibration was developed as part of this study (fig. 5) and allowed the user to input test information to be saved as the title of the data log file (e.g., Replication 1, Torque 1). PTO speed (rev·min^{-1}) and voltage corresponding to torque (V) were displayed to the user in real-time with a table of values to be saved to the log file. The Log Data Boolean control allowed the user to log the raw 1 Hz data during specific test durations. When the Stop control was selected the data in the table were published to the data log file and the VI terminated was execution. Under field conditions the raw data would be sampled at a higher rate dependent on the maximum PTO speed of the instrumented tractor (e.g., 1000 PTO rpm ≈ 16.6 Hz) to allow for PTO engagement and disengagement loads.

Torque and Speed channels for the DUT were set up in NI Measurement and Automation Explorer (NI MAX). This prevented the user from changing the physical channels during testing. In the block diagram (Appendix I), the channels from NI MAX were initialized with the log file information. A while loop allowed the program to continue to run until the Stop control was selected.



(b)

Figure 4. (a) AGCO Allis tractor with NCTE torque sensor connected to the DS (PTO shield extended), (b) NCTE torque sensor with PTO shield retracted.

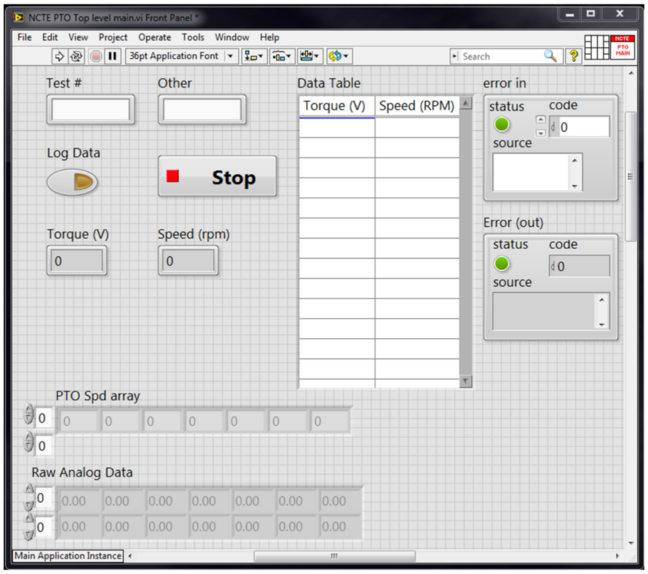


Figure 5. Front panel of LabVIEW program used for calibration of the PTO DUT.

Calibration Procedure

The DUT was calibrated using the NTTL's Dyno, which provided calibration conditions similar to that of a field operation at a fairly steady rotational speed.

Calibration began with the tractor starting the PTO at low idle (~600 PTO rev·min^{-1}). A load of 220 N·m was applied to limit the run-out on the unloaded shaft. As the PTO speed was increased to approximately 750, 900, 1050, and 1100 rev·min^{-1} loads 380, 570, 1070, and 1350 N·m respectively were applied to prevent eccentricity in the shaft during the warmup cycle. A PTO speed of 1100 rev·min^{-1} was achieved when the tractor was at rated engine speed (RES, 2200 rev·min^{-1}), indicating a PTO gear ratio of 2:1.

The governor was set to wide open throttle. After all the tractor power systems had become stable, a 60 s average was used to obtain the values for torque and speed at RES (Code 2 section 4.1.1.3.1.1, OECD, 2016). Using the Dyno controller, the torque applied through the Dyno was set to obtain the points outlined (85%, 64%, 43%, and 21% of the torque at RES) in Code 2 sections 4.1.1.3.1.2 to 4.1.1.3.1.5 (partial loads) of OECD Code 2. The unloaded condition in section 4.4.4.3.1.6 was not used for safety concerns as the sensor shaft could potentially fail because of eccentricity in the rotation of the sensor. Three replications of this calibration process were obtained with 85% of the torque at RES measured first in each replication. The process continued to the next lower partial load until all four points were collected in the replication. The 1 Hz DUT voltage averaged over 60 s at each corresponding measured Dyno torque 60 s average was utilized to determine the calibration curve.

Calibration Verification

Torque at full load and varying speed (lug run) (section 4.1.1.2, OECD, 2016) was greater than the partial loads due to torque rise. The equation obtained from the calibration was applied to the DUT voltage output values obtained during the lug runs. The lug runs began with the engine governor set at wide open throttle. The Dyno controller applied a load to the PTO until the engine speed was reduced to RES. Additional torque was applied by the Dyno controller to reduce the engine speed in 100 rev·min^{-1} (50 PTO rev·min^{-1}) increments. A 60 s average was obtained for each engine speed down to 50% of RES (1100 engine rev·min^{-1}, 550 PTO rev·min^{-1}). After each load/speed change, the tractor engine and Dyno were allowed to run until all signals demonstrated stability for at least 1 min before the data for the 60 s averages were taken. The lug run was replicated 3 times for statistical evaluation of the calibration verification. The DUT and Dyno torque values for a given load/speed setting were compared across the 3 lug runs.

Experimentally, the different PTO speeds were considered treatments, and the differences of the 60 s torque averages (Dyno torque – DUT torque) were considered the observed responses to the treatments. The three differences from each PTO speed (one from each replicate) were considered a sample from a population, and a Student's t-test was used to determine if the means of any of the samples was significantly different from zero (H_0: torque difference = 0). The Student's t table value of 4.303 [two-tailed distribution, probability level of 0.05, two degrees of freedom (3 replicates)] was compared to the Student's t-test statistics calculated from the sample data.

Results and Discussion

The raw voltage data from the DUT that were collected during the partial load tests were associated to torque values from the Dyno. A linear calibration regression (m = -1240.9, b = 6412.5) with a strong coefficient of determination (R^2=0.9999) was fitted (fig. 6) using the four torque loads over the 3 replications.

Table 1 shows the 60 s average voltage and torque values from the DUT and Dyno respectively. Each treatment represented a load condition as outlined in OECD Code 2.

After the calibration equation (eq. 1) was determined, the equation was then applied to the DUT voltage measured during the lug runs to verify the calibration equation.

$$\mathrm{T} = \left(-1240.9 \frac{N \cdot m}{V} * x \right) + 6412.5\ N \cdot m \qquad (1)$$

where

T = torque measured by the Dyno (N·m),

x = voltage measured by the DUT (V).

Table 2 shows the torque values and differences obtained during the full load and varying speed lug run tests used in the verification of the calibration. A graphical presentation of the torque values with PTO speed is shown in figure 7. The first replicate (lug run) had the largest torque difference (23.0 N·m) and range of torque differences (3.2 to 23.0 N·m, 3.2 to 1.34%), and the largest average of the torque differences within a replicate (12.5 N·m). The largest variation in torque differences among the replicates at each PTO speed (30.5 N·m) occurred at the PTO speed of 850 rpm, at peak torque.

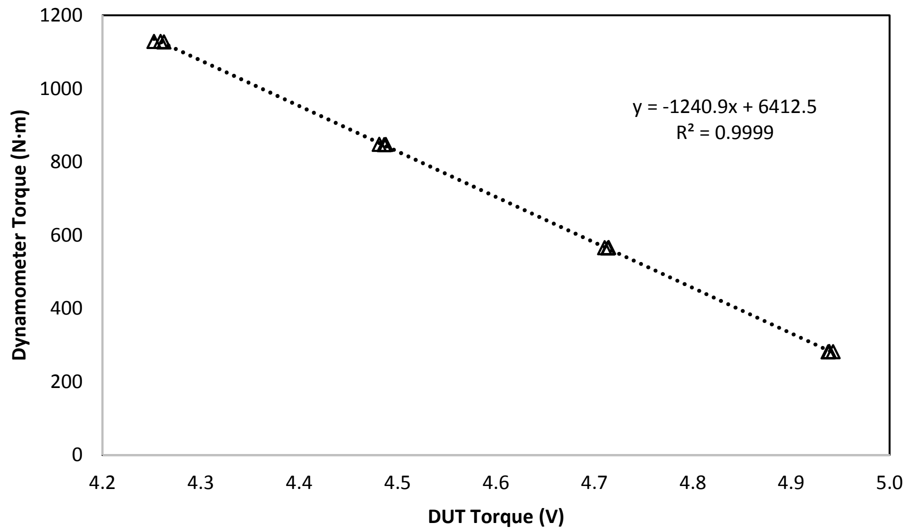


Figure 6. Partial loads used to determine calibration equation for the NCTE torque sensor on the tractor PTO.

Table 1. Calibration points from partial loads.

Replication	% of RES Torque	DUT Torque (V)	DS Torque (N·m)
1	85%	4.2523	1128.82
	64%	4.4813	847.78
	43%	4.7104	565.87
	21%	4.9375	281.62
2	85%	4.2589	1128.57
	64%	4.4862	847.27
	43%	4.7136	565.01
	21%	4.9385	282.46
3	85%	4.2623	1127.49
	64%	4.4879	847.69
	43%	4.7143	566.35
	21%	4.9425	282.23

The largest torque difference on a percent basis was less than 1.35% from the first replicate, and less than 0.85% for the second and third replicates. OECD Code 2 (OECD, 2016) has permissible measurement tolerances of ±1.0% for force, and ±0.5% for distance, so using the larger of these measurement tolerances for torque yielded a measurement tolerance of ±1.0% for the controlled laboratory condition of the OECD tractor test station. Allowing a 50% increase in this measurement tolerance for field research equipment yields a measurement tolerance for torque of ±1.5%, which was larger than all of the percent torque difference values obtained in this experiment. NCTE claimed torque accuracy within ± 0.5%. It was unclear if this statement pertained to a static calibration (e.g., no rotation) or a steady state calibration (e.g., rotating with constant load).

None of the samples of torque differences at each PTO speed had a mean that was significantly different than zero. The interpretation of this result is the two-tailed Student's t-

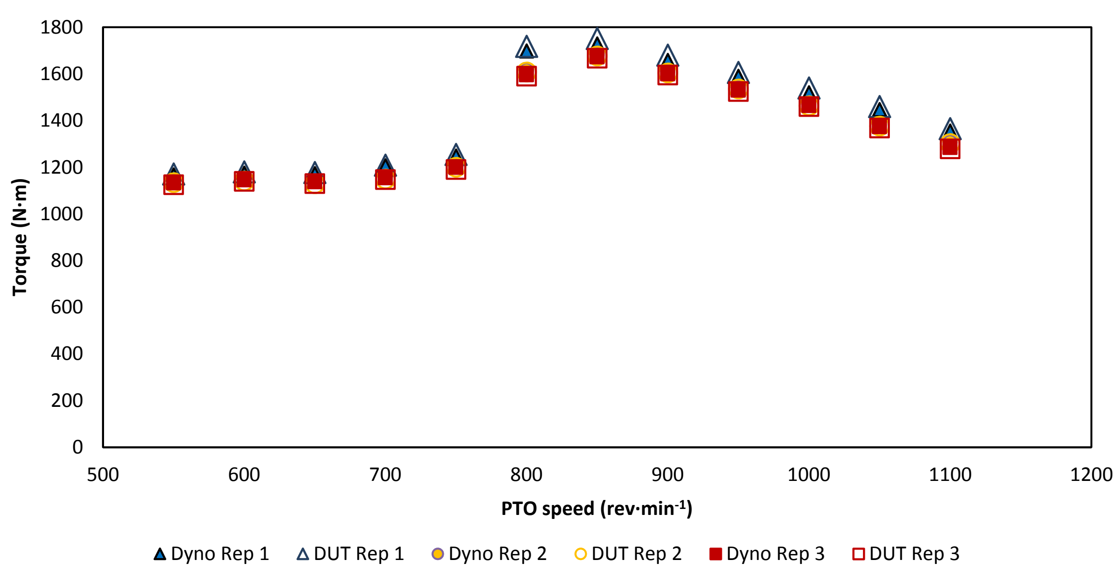


Figure 7. Full load varying speed test results used for verification of the DUT calibration.

Table 2. Dyno vs. DUT torque, full load varying speed test.

Replication	PTO Speed ($rev \cdot min^{-1}$)	Dyno Torque (N·m)	DUT Torque (N·m)	Torque Difference (N·m)	Torque Difference (%)
1	1100	1355.22	1365.37	-10.15	-0.75%
	1050	1446.91	1459.85	-12.94	-0.89%
	1000	1518.90	1539.30	-20.39	-1.34%
	950	1589.81	1606.26	-16.45	-1.03%
	900	1657.79	1680.09	-22.29	-1.34%
	850	1728.39	1751.36	-22.97	-1.33%
	800	1698.20	1717.87	-19.67	-1.16%
	750	1247.78	1254.42	-6.64	-0.53%
	700	1205.80	1209.02	-3.22	-0.27%
	650	1172.19	1176.94	-4.75	-0.41%
	600	1174.13	1179.68	-5.55	-0.47%
	550	1166.96	1171.27	-4.31	-0.37%
2	1100	1308.22	1301.35	6.88	0.53%
	1050	1383.84	1376.13	7.71	0.56%
	1000	1470.76	1463.54	7.22	0.49%
	950	1542.78	1535.51	7.26	0.47%
	900	1611.83	1603.79	8.05	0.50%
	850	1684.20	1676.68	7.52	0.45%
	800	1616.22	1608.06	8.16	0.50%
	750	1207.76	1199.76	8.00	0.66%
	700	1158.45	1149.18	9.27	0.80%
	650	1137.78	1128.92	8.86	0.78%
	600	1148.89	1140.48	8.41	0.73%
	550	1143.46	1134.20	9.26	0.81%
3	1100	1284.08	1279.06	5.02	0.39%
	1050	1373.31	1368.24	5.07	0.37%
	1000	1464.29	1459.99	4.29	0.29%
	950	1530.12	1524.73	5.39	0.35%
	900	1600.22	1595.19	5.03	0.31%
	850	1672.40	1667.28	5.12	0.31%
	800	1595.82	1590.23	5.60	0.35%
	750	1198.88	1190.34	8.55	0.71%
	700	1154.57	1147.19	7.38	0.64%
	650	1137.56	1129.82	7.73	0.68%
	600	1145.70	1139.11	6.59	0.58%
	550	1132.51	1124.84	7.67	0.68%

test indicated with 95% probability that the Dyno torque values and DUT torque values were not significantly different.

Summary and Conclusions

A data acquisition system was implemented to measure and record torque from a tractor PTO shaft without modifying the tractor or implement shafts. The NCTE torque sensor was used for steady state calibration due to the tighter tolerances in the coupler compared to the Datum Electronics torque sensor. The OECD Code 2 PTO test at varying load was used to measure torque at partial loads to determine a calibration equation for the torque sensor. The varying load data provided a linear ($m = -1240.9$, $b = 6412.5$) calibration equation with high coefficient of determination ($R^2 = 0.999$) to calculate the torque of the DUT from the torque sensor voltage. The OECD Code 2 PTO torque at full load and varying speed procedure was then used to verify the calibration equation. Differences in torque measurements obtained from the Dyno and the DUT were not statistically significantly different from zero using a two-tailed Student's T-test at an alpha level of 0.05. The torque differences obtained during the first replicate (lug run) were the largest of the three replicates, and ranged from 3 N·m (0.27%) to 23 N·m (1.33%). These differences were within 1.35% of the torque measured. Torque differences from the second and third lug runs had smaller torque differences, within the range from the first lug run. As the OECD Code 2 measurement tolerances for force is ±1.0% in laboratory settings and allowing a 50% increase in this tolerance for torque in field conditions, it was determined that a torque tolerance of ±1.5% would provide reliable tractor PTO torque measurements under field conditions. All torque differences obtained during the verification testing using the OECD Code 2 PTO full load and varying speed test procedure met the ±1.5% torque measurement criteria.

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Appendix I–LabView Block Diagram

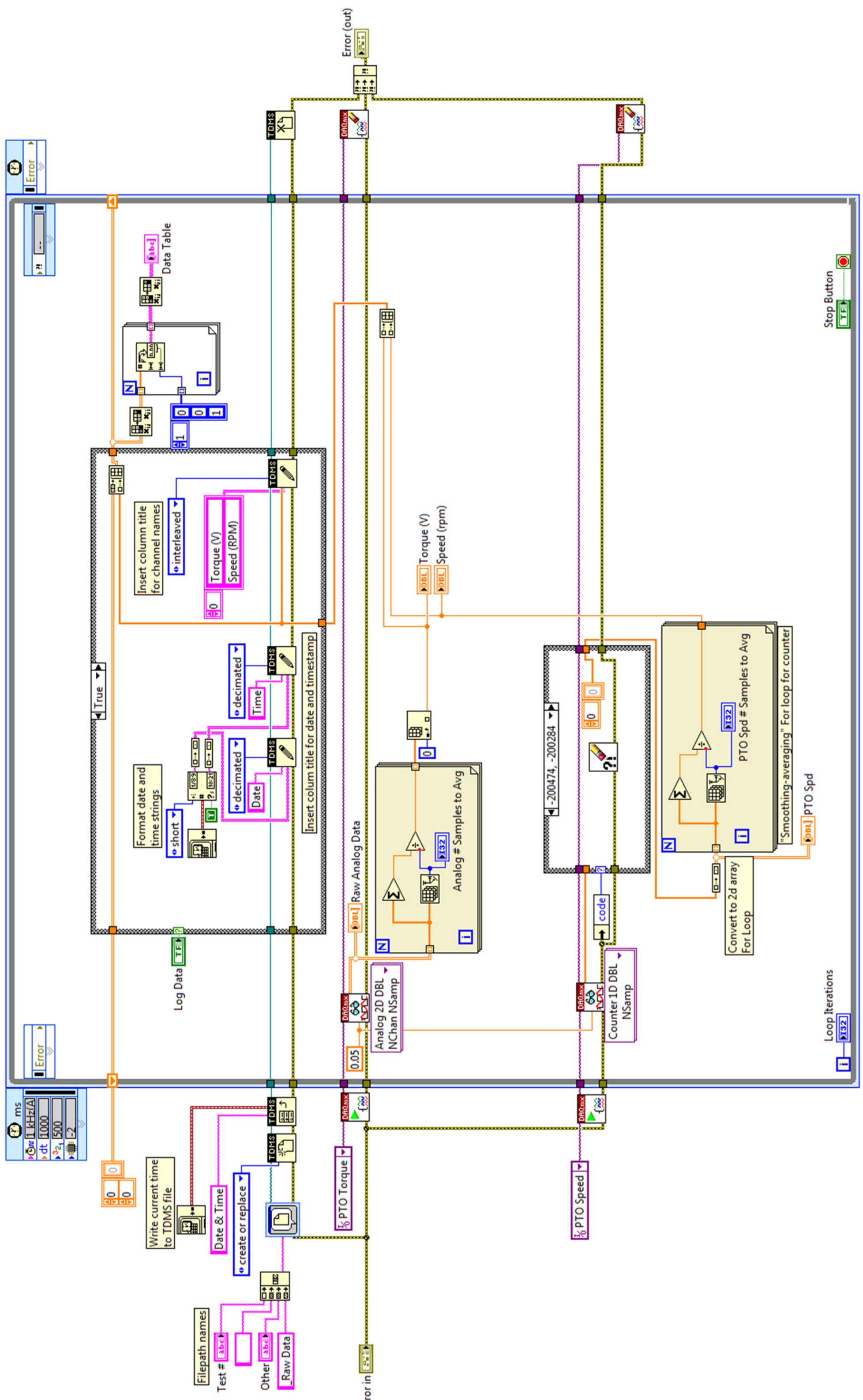

Figure 8. Block Diagram of LabVIEW program. Illustrates the initialization, reading, logging, and termination functions of the VI.